III.D.3 Solid Oxide Fuel Cell Manufacturing Cost Model: Simulating Relationships between Performance, Manufacturing, and Cost of Production

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Objectives

The objective of this project within the Solid State Energy Conversion Alliance (SECA) Core Technology Program (CTP) was to develop analysis methods and computational codes for analyzing solid oxide fuel cell (SOFC) production process issues in order to aid development of optimal production process methods, rates, and controls. The National Energy Technology Laboratory (NETL) sought development of a model with the capability to:

- Handle all key SOFC stack components, including ceramic cells and interconnects;
- Relate manufactured cost to product quality and likely performance, taking into account manufacturing tolerances, product yield, and line speed; and
- Address a range of manufacturing volumes ranging from tens to hundreds of megawatts per year.

Approach

- In Task 1, the overall project approach was presented to the SECA teams to solicit their inputs on how to tailor the cost model to their needs and what issues should be addressed in this phase of work
- In Task 2, the manufacturing cost model was linked to a performance/thermal/mechanical model and a statistical model of material failure to calculate process yields and performance as a function of electrode electrolyte layer thicknesses. The impact of economies of scale on the manufacturing cost was also modeled. The results of the analysis and the model assumptions were discussed with the SECA teams, and their feedback was incorporated into the analysis.
- In Task 3, a final report was prepared.

Accomplishments

- A manufacturing cost model developed in 1999 was updated and enhanced by linking it to a performance/thermal/mechanical model that calculated average power densities and stress distributions in the stack as a function of stack parameters and operating conditions. A more detailed analysis of quality control costs was incorporated in the model.
- The statistical material failure models developed by Oak Ridge National Laboratory (ORNL) were incorporated into the model to calculate yields as a function of stresses during manufacturing and power generation. The effect of electrode electrolyte assembly (EEA) defects on stack yield was estimated.
- The impact of economies of scale on stack cost was modeled.
- Several but not all of the SECA teams provided inputs to the project on an individual basis. The Teams preferred this mode of input versus the workshop format suggested in the proposal.

Future Directions

This project was not continued into Phase II; however, recommendations from the Teams and NETL for future cost analysis included:

- Alternative production techniques to tape casting and screen printing
- Coating processes for interconnects with 3-D flow channels
- Seal and manifold designs
- Balance-of-plant components, particularly any high-temperature components such as recuperators

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Introduction

The National Energy Technology Laboratory (NETL) has a long history in high-temperature fuel cell technology development. The assessment of manufacturing technologies and cost has been an integral component of the technology development due to the criticality of both to the commercialization of fuel cells in a competitive marketplace. In 1999, TIAX [1] (as the Technology and Product Development sector of Arthur D. Little) conducted a technology and cost assessment of anode-supported planar SOFC technology with metallic interconnects. The cost of this lower-temperature (<800^oC) SOFC technology was compared to a high-temperature (1000^oC) planar all-ceramic design. For the low-temperature planar technology with metallic interconnects, a manufacturing cost projection of \$430/m^2 was obtained through an activities-based cost model. For an assumed power density of 500 mW/cm^2, this translates into a cost of \$86/kW for materials and processing, significantly less than the all-ceramic high-temperature stack with a cost of \$377/kW. Several factors contributed to the lower overall stack cost:

- Lower temperature permitted the selection of a much less expensive interconnect material, ferritic stainless steel.
- Anode support of the cell allows use of a thin electrolyte, leading to higher power density and much less yttria stabilized zirconia (YSZ) material.

The lower projected overall cost for low-temperature SOFC technology increases the likelihood of commercial success of SOFCs.

Using the previously developed cost model as the starting basis, NETL-SECA wished to develop analysis methods and computational codes for analyzing issues in SOFC production. The methods and codes are ultimately to be used in development of optimal production process methods, rates, and controls.

Approach

In this phase of the project, the emphasis was on demonstrating the capabilities of the cost model to the SECA Industry teams and getting their inputs on critical issues. The proposed approach involved workshops to gather these inputs. However, after discussions with the SECA teams, we found that they preferred the use of individual meetings rather than collective workshops as a means of collecting information. In addition, the teams did not want to access the cost model through an internet-based user interface. For this project, only non-proprietary discussions were held, and the cost model demonstration was conducted using generic information in the public domain. Several of the SECA teams provided inputs on topics of interest for this analysis and feedback on the draft final presentation. After the initial face-to-face meetings, subsequent discussions were conducted at SECA meetings or over the phone.

For purposes of this project, a cost model developed in 1999 for planar metal-supported stacks was used as the basis. The results and assumptions of the 1999 project were updated, and the cost model was augmented with a SOFC performance model to calculate power density, utilization, temperature gradients, and mechanical stresses in the stack, the latter during steady-state operation and thermal cycling. Addition of this capability permits one to evaluate the impact of improvements in electrochemical performance, changes in power density as the stack design changes (e.g., thickness of individual layers, changes in active area and flow field design), and changes in material properties. The model was also used to calculate maximum stresses on the materials, and it was compared with failure curves to estimate mechanical failures due to cracking. In contrast, the 1999 model simply selected an average power density and assumed that the utilization could be achieved and the materials would survive any stresses arising from thermal gradients.

Results

The analysis was based on the stack design assumed in the 1999 study (as a baseline to provide continuity) and a production volume of 250 MW per year. Conventional SOFC materials (i.e., nickel cermet anode, 8 YSZ electrolyte, and lanthanum strontium manganite cathode) with nominal anode/electrolyte/cathode thickness of 700/10/50 microns, respectively, were used to develop a bill-of-materials. A rolled formed ferritic stainless steel was assumed for the interconnect; however, a stabilizing conductive coating was not used. In this demonstration, we focused only on the active materials and the interconnect. The seals and manifolds were excluded from this cost analysis.

For a fuel (reformed natural gas) utilization of 85%, cell voltage of 0.7 V, maximum temperature gradient of 150°C across the stack, maximum stack temperature of 800°C, and a contact resistance of 0.1 Ωcm^2, the performance model calculated a baseline average power density of 470 mW/cm^2. The model kinetic and diffusion parameters were calibrated using single cell kinetic data from the literature. For these operating conditions, the stress conditions resulted in less than 5% cracking of the materials based on failure data from ORNL. Power density increased when using thinner ceramic layers in the cell, reaching a maximum of 570 mW/cm^2 at the minimum thickness allowed for each layer.

Table 1. 2003 Total Stack Factory Cost on an Area Basis ($\$/m^2$). In the co-fire process, the electrodes and electrolyte are sintered in a single step. In the multi-fire process, the anode and electrolyte are sintered first and then the cathode is sintered.

Total Cost (Materials + Processes) ($\$/m^2$)

Co-Fire		\$/m² Material	\$/m² Process
Process Flow Steps	Anode	\$ 123.95	\$ 9.63
	Cathode	\$ 18.22	\$ 7.40
	Electrolyte	\$ 6.01	\$ 6.18
	Interconnect	\$ 118.70	\$ 19.25
	Fabrication	\$ -	\$ 100.99
Sub-Total		\$ 266.87	\$ 143.45
Total		\$410.32	

Multi-Fire		\$/m² Material	\$/m² Process
Process Flow Steps	Anode	\$ 125.92	\$ 9.69
	Cathode	\$ 14.57	\$ 7.07
	Electrolyte	\$ 6.11	\$ 6.21
	Interconnect	\$ 118.70	\$ 19.25
	Fabrication	\$ -	\$ 126.72
Sub-Total		\$ 265.29	\$ 168.93
Total		\$434.22	

Table 2. 2003 Total Stack Factory Cost on a Power Basis (\$/kW)

Total Cost (Materials + Processes) (\$/kW)

Co-Fire		\$/kW Material	\$/kW Process
Process Flow Steps	Anode	\$ 26.29	\$ 2.04
	Cathode	\$ 3.86	\$ 1.57
	Electrolyte	\$ 1.27	\$ 1.31
	Interconnect	\$ 25.18	\$ 4.08
	Fabrication	\$ -	\$ 21.42
Sub-Total		\$ 56.60	\$ 30.43
Total		\$87.03	

Multi-Fire		\$/kW Material	\$/kW Process
Process Flow Steps	Anode	\$ 26.71	\$ 2.05
	Cathode	\$ 3.09	\$ 1.50
	Electrolyte	\$ 1.30	\$ 1.32
	Interconnect	\$ 25.18	\$ 4.08
	Fabrication	\$ -	\$ 26.88
Sub-Total		\$ 56.27	\$ 35.83
Total		\$92.10	

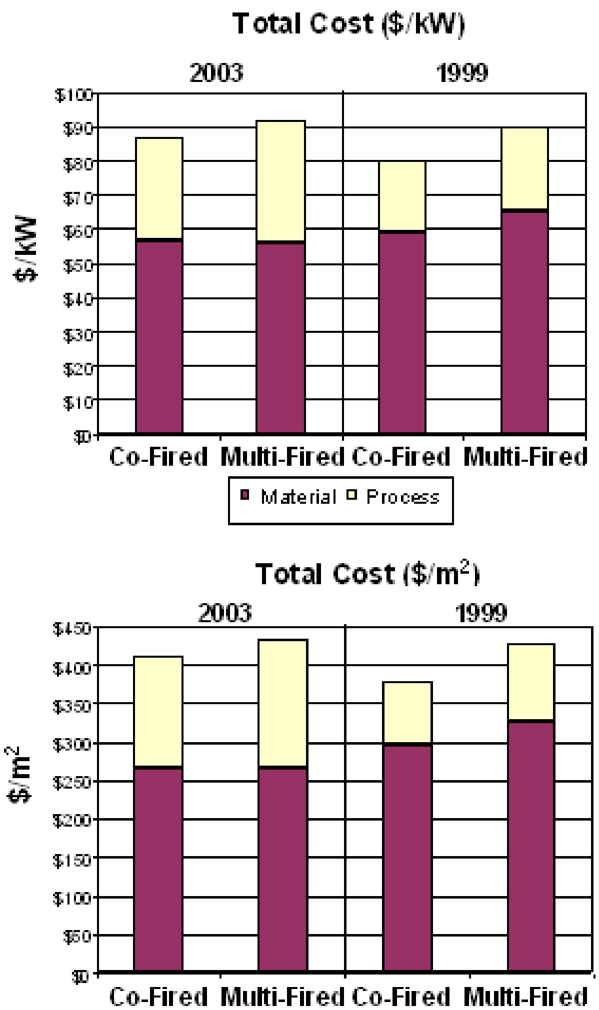

Figure 1. Comparison of 2003 and 1999 Total Stack Factory Cost Projections (250 MW per year production volume)

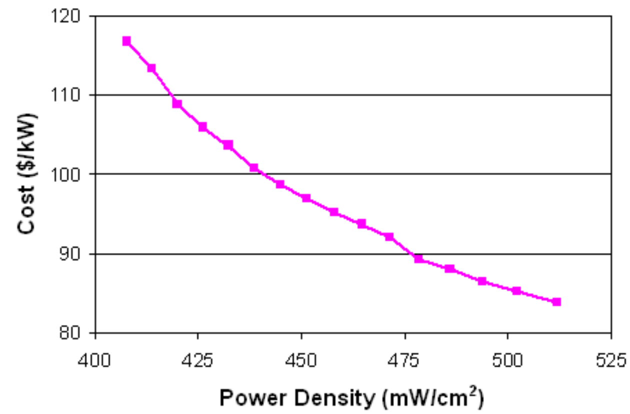

Figure 2. Cost Versus Power Density

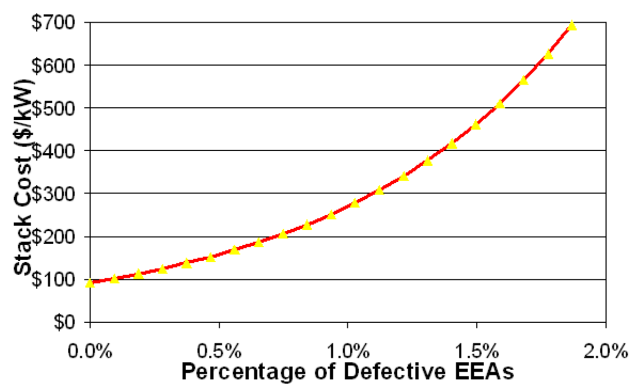

Figure 3. Plot of Stack Cost Versus Percentage of Defective EEAs Getting through Quality Control

The updated analysis of stack cost showed that the 1999 cost projections for planar anode-supported SOFC stacks should still be achievable (Tables 1 and 2, Figure 1). In the present study, the net result of increases and decreases in factors influencing the cost resulted in approximately a 5% increase in cost of the baseline case to $90/kW. Increases in processing costs, primarily driven by the addition of quality control steps, were greater than the reductions in material cost, primarily driven by lower assumed costs for YSZ. The lower power density of the 2003 baseline case further accentuated the increases in cost on per kW basis. The anode and interconnect dominated the stack cost, contributing approximately 90% of the cost. Tables 1 and 2 provide a breakdown of cost on an area and kW basis.

Achievement of high power densities will be important for low cost due to the large contribution (approximately 85% at high production volumes) of materials to the stack cost. The inclusion of a performance/thermal/mechanical model is important for analyses of this type because real kinetic data, ohmic losses, stack design parameters, mass transport limitations, and temperature gradients can be factored into the projected power density without violating utilization assumptions. Minimization of the thickness of the EEA layers will contribute to increased power density with the electrolyte being the most important factor. Figure 2 shows cost as a function of power density. Electrolyte thickness was varied from 5 to 20 µm with a fixed anode (700 µm)

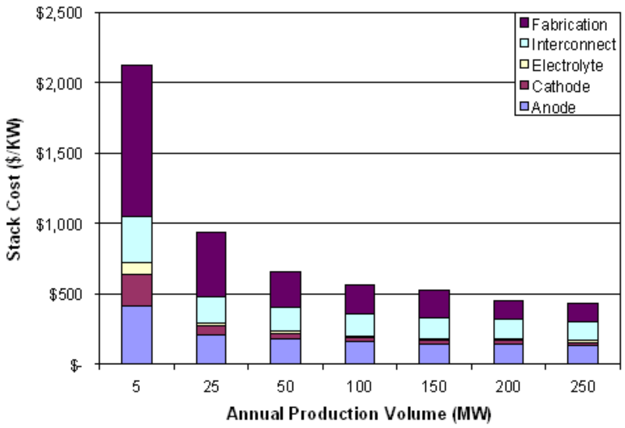

Figure 4. Breakdown of Stack Costs as a Function of Production Volume ($/kW)

and cathode thickness to obtain this variation in power density.

Quality control will be critical to successful assembly of stacks with high yields. If defective EEAs pass through final inspections prior to stack assembly at even a 1 percent level, stack cost could increase by more than a factor of 2 above the baseline projection (Figure 3). The stack yield will be influenced by the number of cells, which can impact decisions on stack voltage and stack interconnect costs for a targeted system voltage.

Significant economies of scale will be realized in increasing the production volume from 5 MW to 250 MW, with approximately 60% of the cost reduction realized in stepping up to 25 MW (Figure 4). For this analysis, reductions in process costs due to higher utilization of capital equipment were a major factor in the decrease in cost.

Conclusions

- The stack costs estimated in 1999 are still achievable. Updating of the model, including process assumptions, material costs, and consideration of quality control processes, resulted in offsetting cost factors.
- The performance model showed that the power density assumed in 1999 was in fact reasonable and consistent with critical assumptions such as fuel utilization, inlet/outlet temperatures, contact resistance, and electrode dimensions. In a materials intensive technology, the realization of target power densities will be critical to meeting cost targets.
- Quality control of the EEAs going into stack assembly will be absolutely critical to achieving high yields and projected costs. Quality control processes must be included in cost projections to reflect important cost contributions.
- Economies of scale do play a significant role in reducing costs; however, 60% of the benefit is realized at one-tenth the maximum volume considered in this study, largely due to higher utilization of capital equipment.

References

1. E.J. Carlson, S.A. Mariano (1999), Assessment of Planar Solid Oxide Fuel Cell Technology, Arthur D. Little, Inc.

FY 2004 Publications/Presentations

1. SECA Core Technology Program Review Meeting, Sacramento (February 2003)
2. Final report presentation to NETL (February 2004)
3. Eric J. Carlson, Suresh Sriramulu, Peter Teagan, Yong Yang, “Cost Modeling of SOFC Technology”, First International Conference on Fuel Cell Development and Deployment, University of Connecticut, Storrs (March 7-10, 2004)
4. Presentation accepted for Fuel Cell Seminar (November 2004)